Computing Tools and Simulations for Accelerators

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DOE Annual Program Review

Overview

- Many simulation application activities in APC
  - utilizing different computational tools
- Here, focus on the tools development and computations that involve
  - large scale computing
  - general codes developed by FNAL/APC or FNAL/APC-led collaborations
    - SciDAC2 COMPASS collaboration
  - computations performed using FNAL/APC tools

But first, a glossary

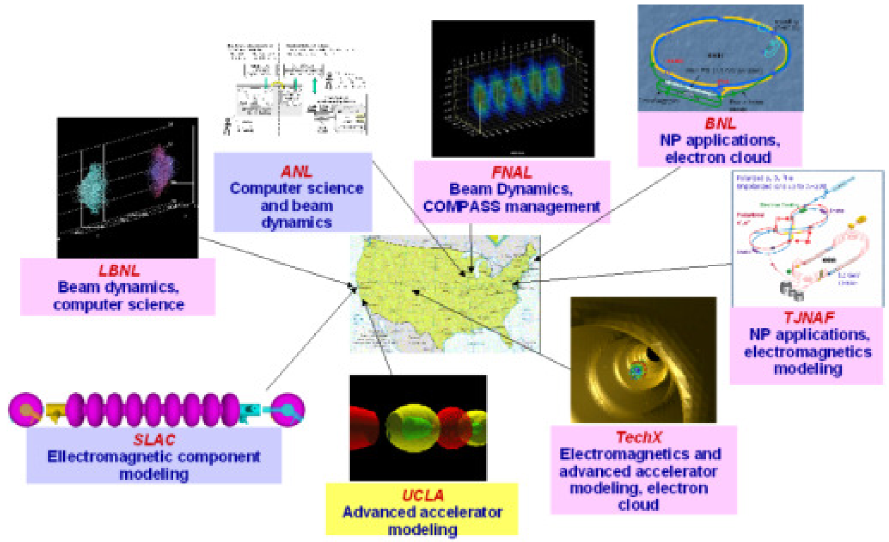
- In case you would like to revisit these slides
  - SciDAC == Scientific Discovery through Advanced Computing, a DOE program
  - AST == Accelerator Simulation && Technology, the SciDAC1 accelerator modeling project
  - COMPASS == Community Petascale Project for Accelerator Science and Simulation, SciDAC2 collaboration
  - HPC == high performance computing
  - CHEF == Collaborative Hierarchical Expandable Framework, FNAL developed optics framework

Milestones

- '01-... multi-particle dynamics (Run-II, ILC)
  - Members of the AST SciDAC collaboration
    - Develop HPC capabilities (the Synergia project)
- '04-... single-particle dynamics (ILC,...)
  - The CHEF project focuses on ILC design
- '06-... electromagnetics (ILC,...)
  - Begin utilization of SciDAC developed tools
- ’07-…, multi-physics tools and applications (Run-II, LHC, ILC,…)
  - Leading the COMPASS SciDAC2 collaboration

The COMPASS collaboration

- COMPASS wins SciDAC2 award in April of ’07, after a 6 month proposal writing and collaboration forging period!
  - Project funded by HEP, NP, BES, and ASCR, at ~$3M/year for 5 years
- COMPASS is the successor of the AST SciDAC1 project
  - But includes more activities & participants



The Community Petascale Project for Accelerator Science and Simulation collaboration

SciDAC Scientific Discovery through Advanced Computing

Fermilab and COMPASS

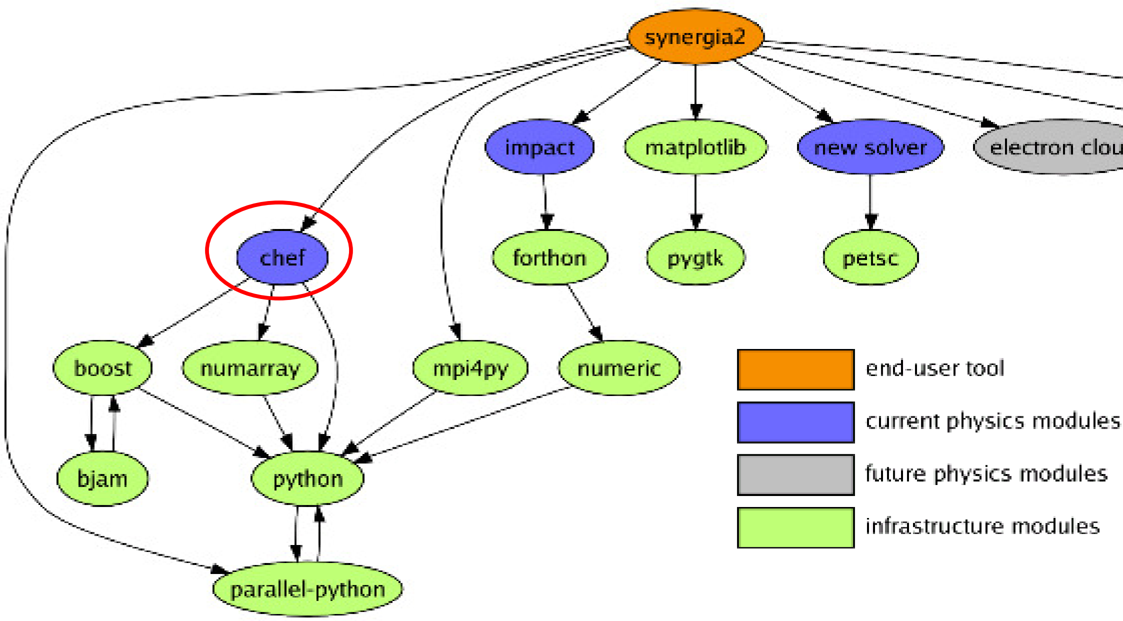
- COMPASS <compass.fnal.gov> aims to provide both HPC accelerator modeling tools and applications
- The APC/CD Computational Physics for Accelerators group
  - leads the collaboration
  - plays a major role in the development of beam-dynamics tools and applications
  - participates in electromagnetics applications relevant to the FNAL program
- FNAL COMPASS funds ~$475k/year for duration of project (FY06 @ $150k/year)

FY07 activity focus

- Utilize mature 3D space-charge capabilities
  - Finalize Booster studies & study ILC DR and RTML
- Develop realistic multi-physics tools for Tevatron simulations (3D beam-beam + impedance)
- Study ILC Low Emittance Transport design
  - Adapt/develop CHEF tools and applications
- Extend Synergia2, our parallel beam dynamics framework, to enable multi-physics capabilities
- Engage in electromagnetics modelling activities, focusing on ILC
  - Utilize and extend existing tools

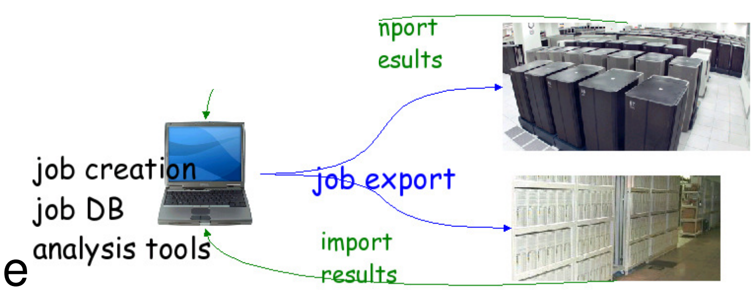
Fermilab SciDAC development: the Synergia framework

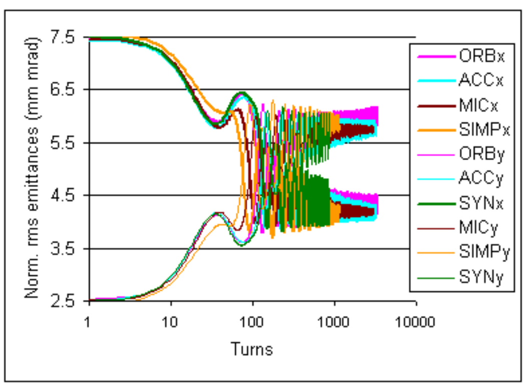
PAC07, TUZBC02



Synergia1: user interface and space-charge

Synergia2: Multi-physics, state of the art numerical libraries



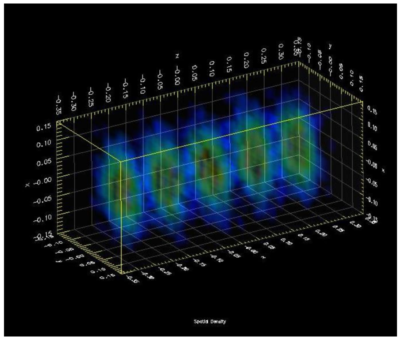


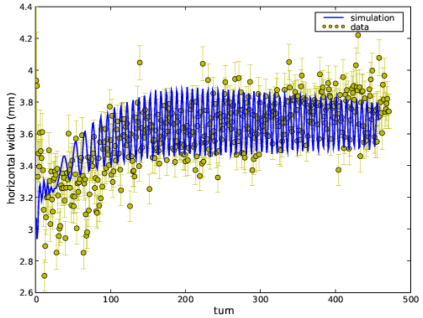
Synergia: mature code (JCP06), participated in International space-charge benchmark effort lead by I.Hofmann

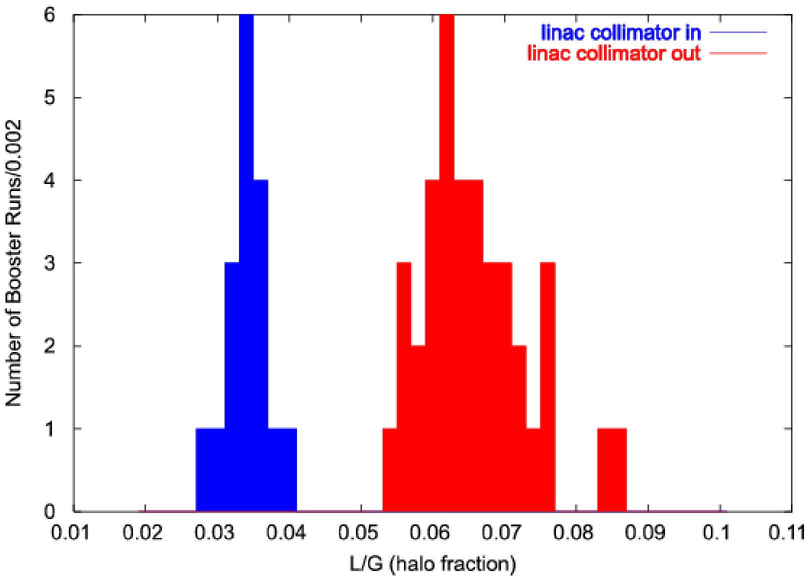
Activity at 1.3 FTE

Finalize Booster studies

- Utilize Synergia simulations to quantitatively characterize halo generation in the Booster
  - New technique for halo characterization using beam shape (NIMA570:1-9,2007)
- Effort @0.5 FTE, plus grad student

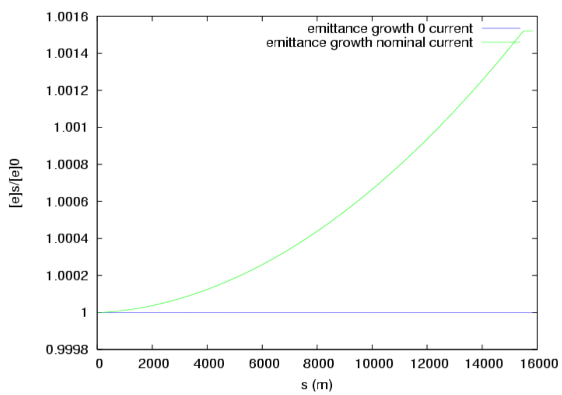


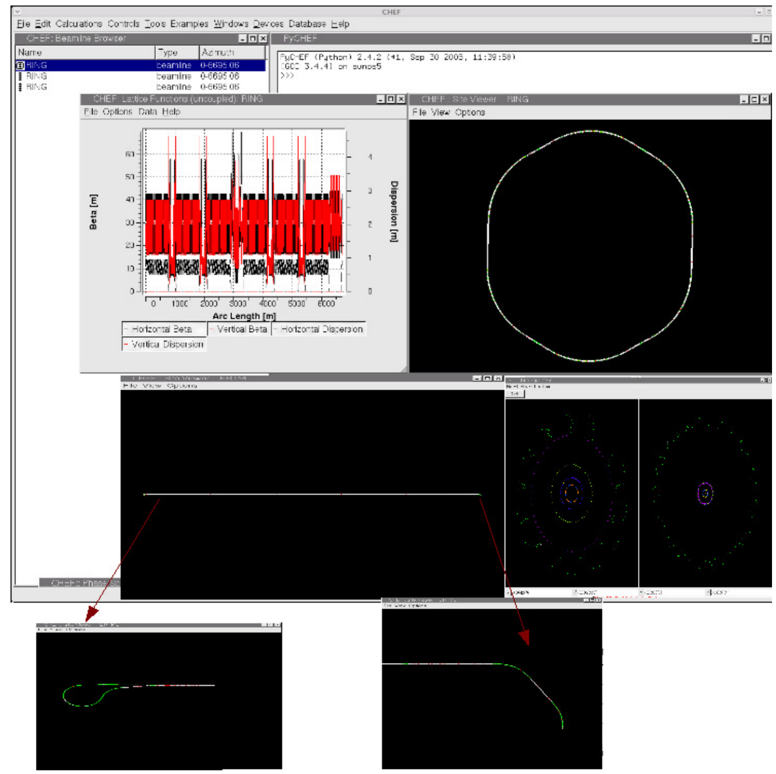


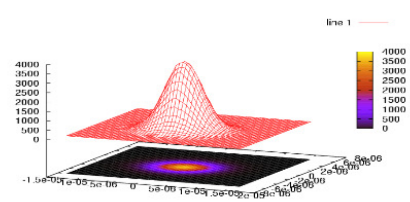


ILC RTML and DR

- Study space-charge effects (halo creation, dynamic aperture) using Synergia (3D, self-consistent).



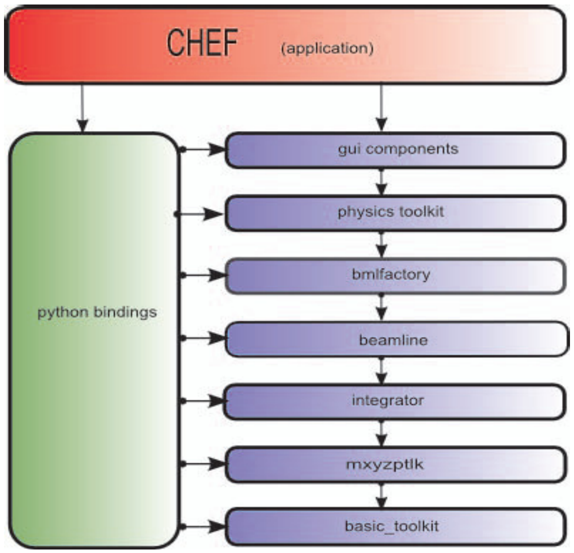


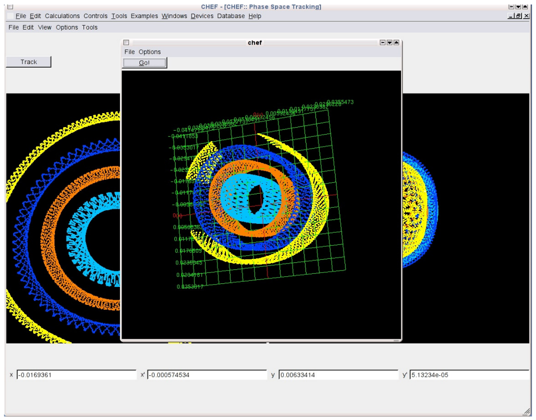


  - Activity level at 1FTE

CHEF

- Started in mid-2003, with the goal to develop a
  - Convenient, intuitive, interactive code for general purpose **optics** computations
- General framework applicable to problems relevant to future machine design.
- Code base currently used at FNAL
  - to study emittance preservation in the ILC. In FY07 developed linac specific functionality (e.g. wakefields, RF structures).
  - and in Synergia (3D space charge framework).

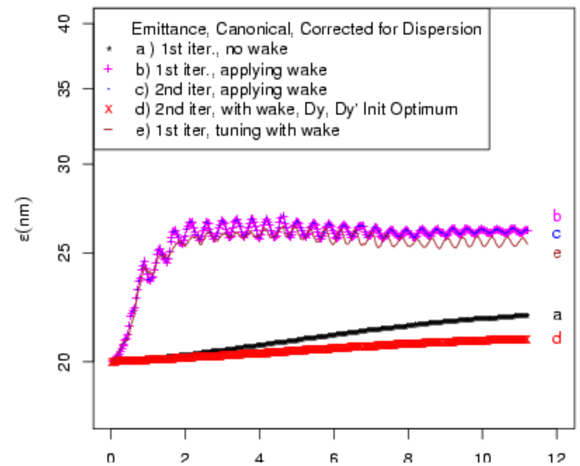


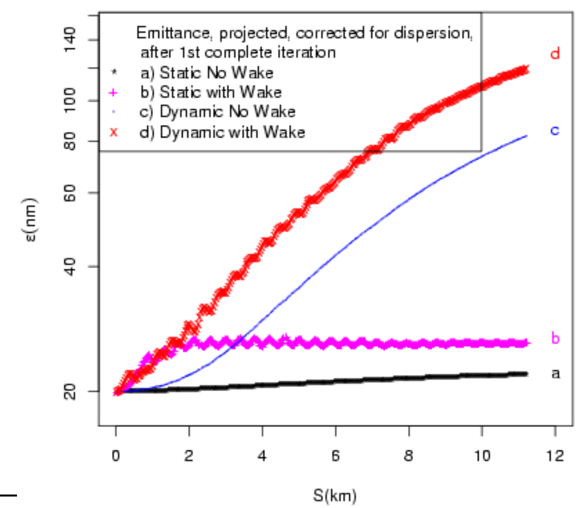


Activity @ 1.5 FTE level

CHEF ILC Main Linac applications

- Study of static tuning of misalignments in the ILC Main Linac
  - Confirmation of results obtained by other codes.
- Begin study of steering performance with dynamic effects
  - Implement such effects in CHEF
- Utilize FermiGrid resources
- Results reported at PAC07 (THPMN104), see also poster by N. Solyak
- Effort level: 1 FTE





Detailed application example: Tevatron beam-beam simulations

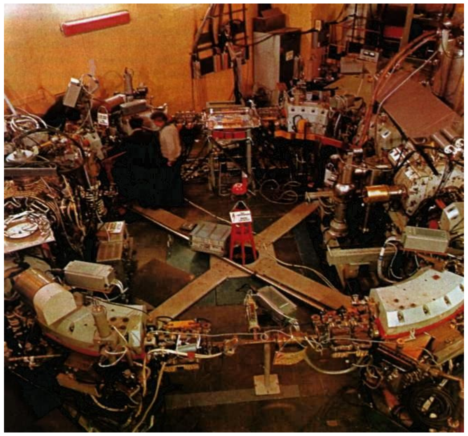
- Motivation: comprehensive simulation of instability sources and their effects
  - strong-strong beam-beam interactions
  - impedance and head-tail instabilities
  - Multi-bunch collisions
    - Each Tevatron bunch sees 2 head-on IPs + 136 long-range IPs
  - Need simulation which includes all relevant effects

- Coupled motion
- Helix trajectory
- Beam-Beam
- Impedance
- Chromaticity
- Multiple-bunch interactions

- Extend BeamBeam3D (SciDAC)

Activity level @ 1FTE

3D strong-strong beam-beam model validation



Use data from VEP-2M: $e^- e^+$ at 500 MeV with comparable vertical and longitudinal spatial dimensions

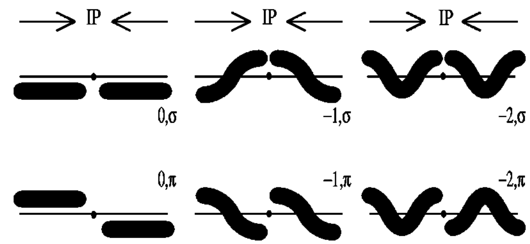
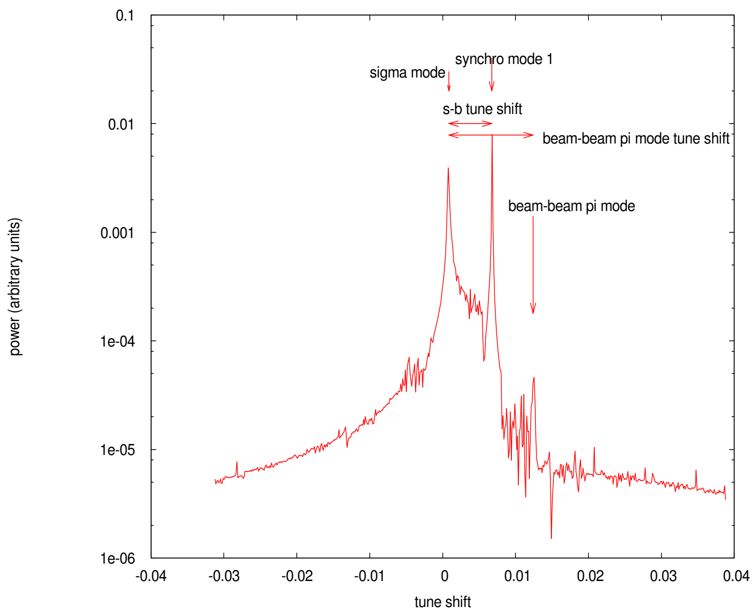
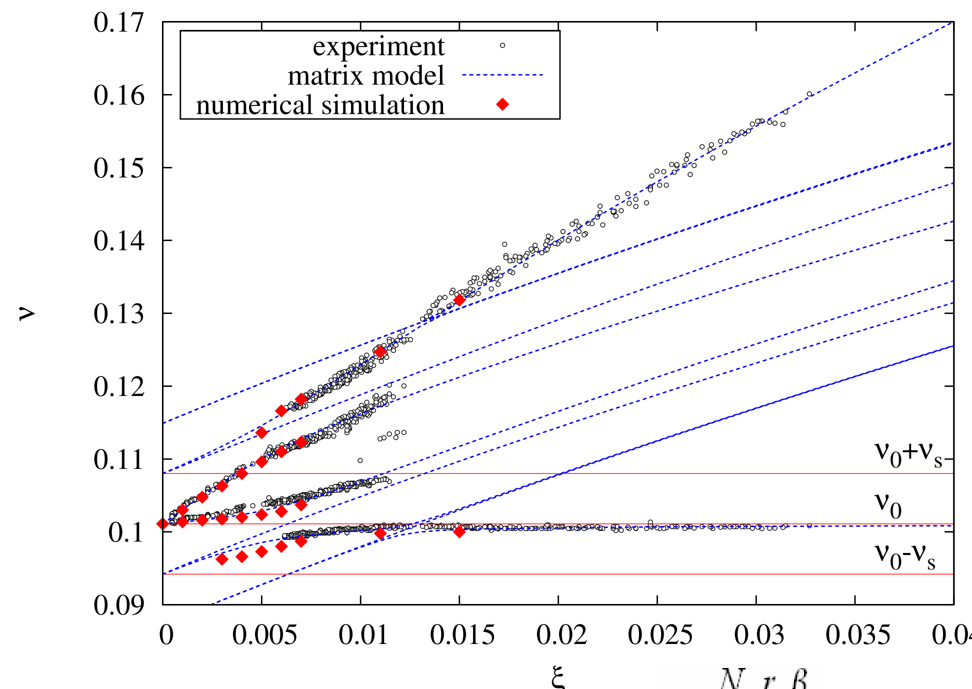


FIG. 1. Notation for the synchrobetatron modes of colliding bunches.



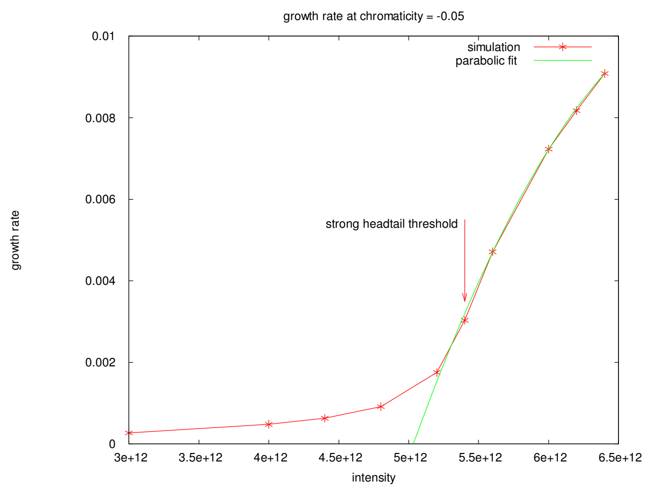


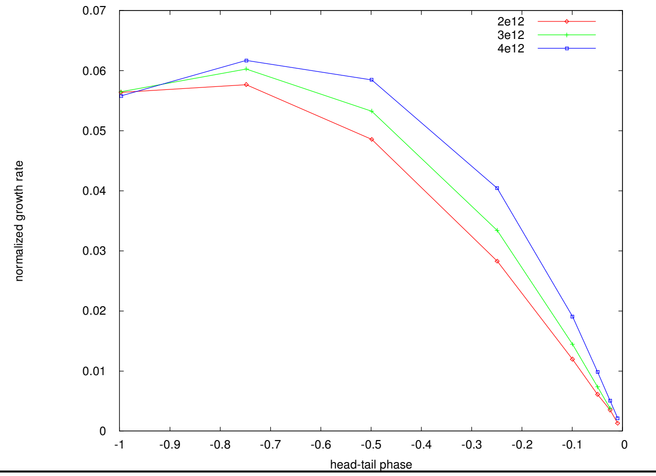
$$\xi = \frac{N_e r_e \beta}{4\pi \gamma \sigma^2}$$

Impedance model validation

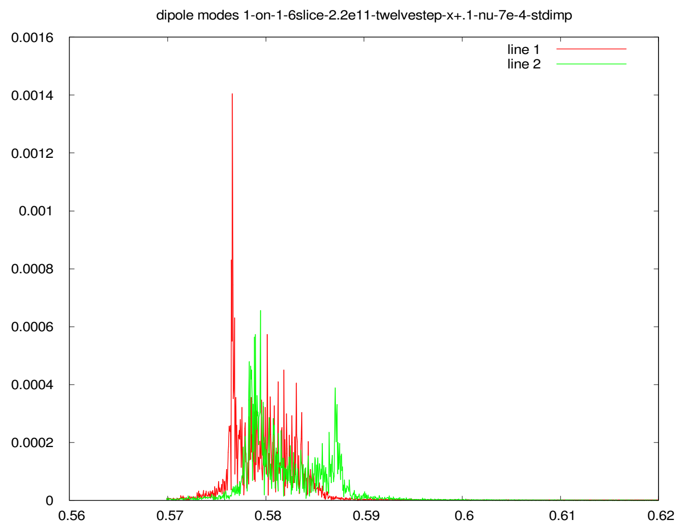
- Compare simulation to expected behavior:
  - Strong head-tail shows the expected parabolic growth at threshold
  - Weak head-tail obeys universal curve for normalized growth rate versus the head-tail phase

$$\text{head-tail phase} \stackrel{\text{def}}{=} \chi = \frac{\xi \omega_\beta \hat{z}}{c\eta} = \frac{2\pi \xi Q_\beta \hat{z}}{L\eta}$$

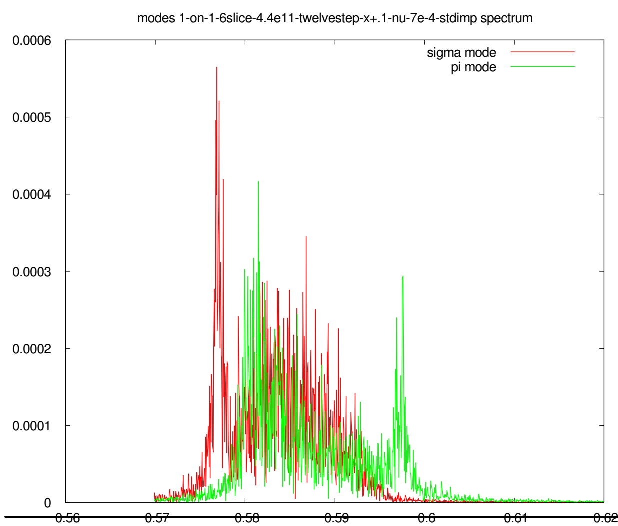




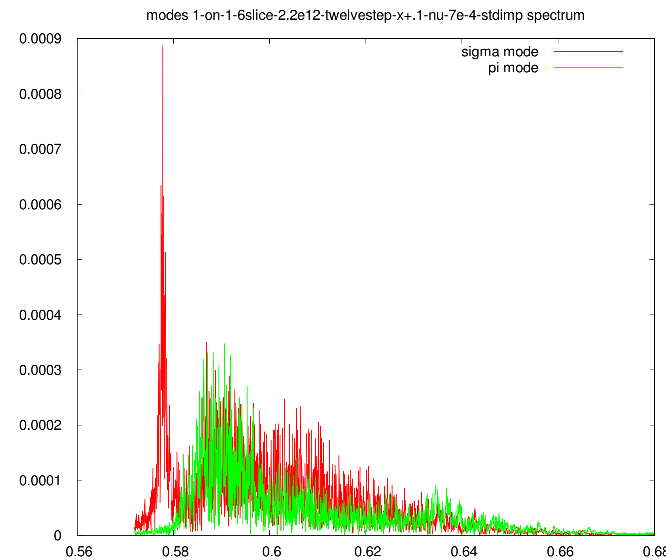
Put it all together: one-on-one bunch Tevatron simulations



"nominal*" beam



4 times "nominal" beam



10 times "nominal" beam

*"nominal" == pbar = p

Effects not enough to create beam instability. Need even more realistic model!

Add more realism

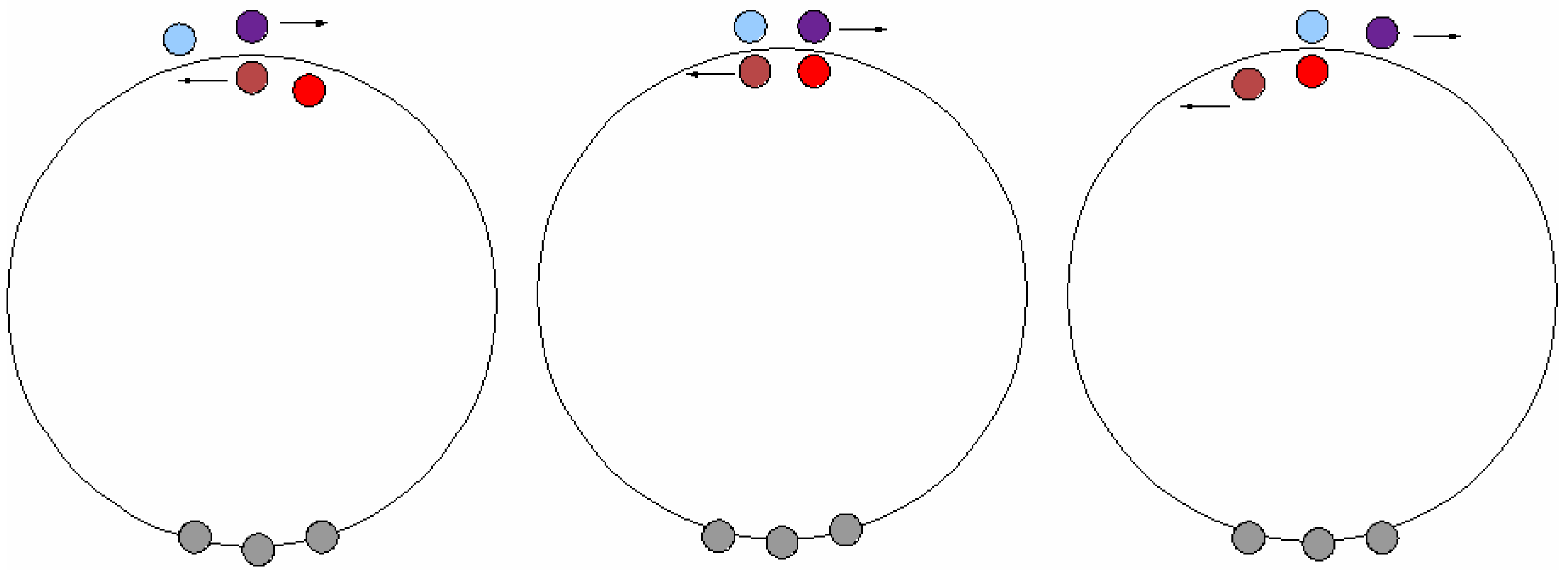
Try multiple bunch run

1 head-on + 2 long-range + 3 reflected long-range IPs

Distance from head-on IP to first long-range IP = 10.5 RF bucket lengths = 59.3 m

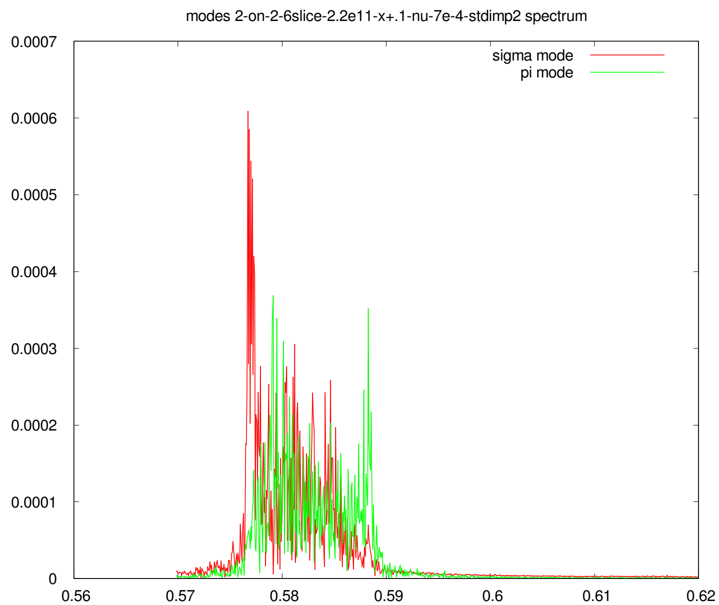
beam separation at adjacent long-range Ips ~0.8 mm

beam separation at reflected IPs ~ 3.5 mm



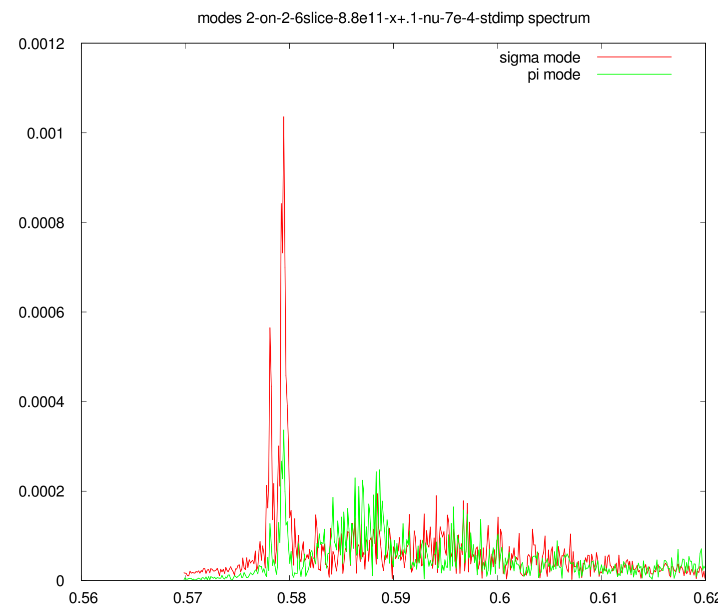
Reflected IPs

2 on 2 bunches, with nominal impedance

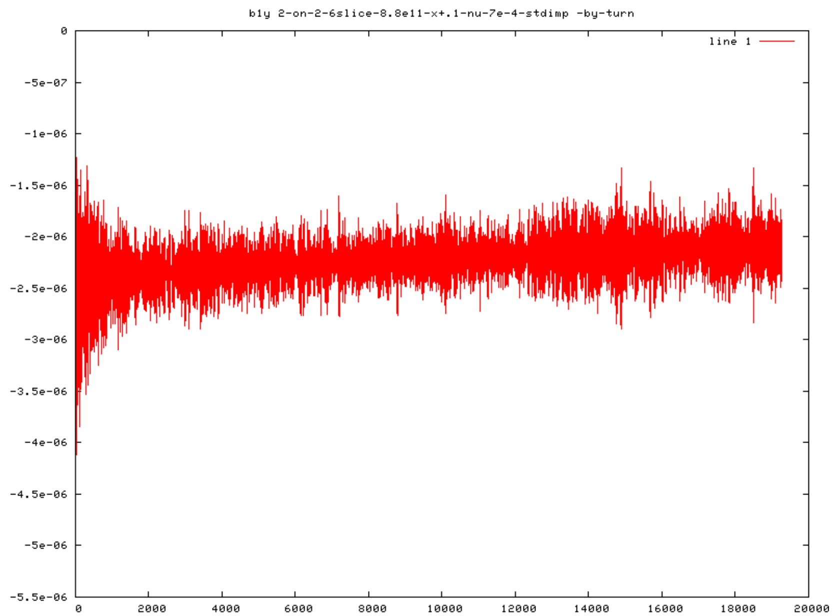


"Nominal" bunch intensity. Peak broadening is seen due to multi-bunch interactions

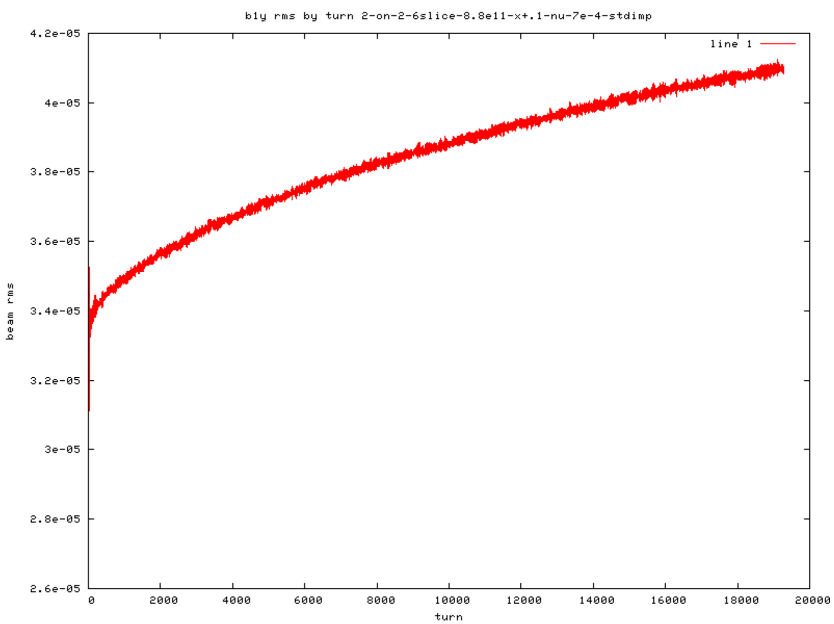
4 times "nominal" bunch intensity. The pi mode cannot be resolved anymore.



Starting to see instability?



After 20k turns (~0.5 s @ flattop), the beam size is increased by ~20%



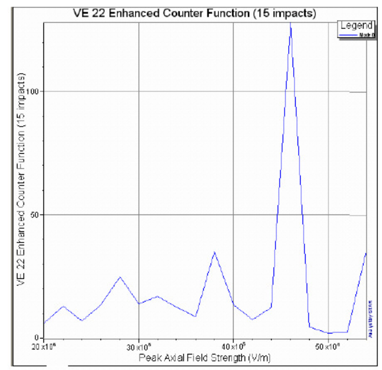
and the beam position appears to be changing.

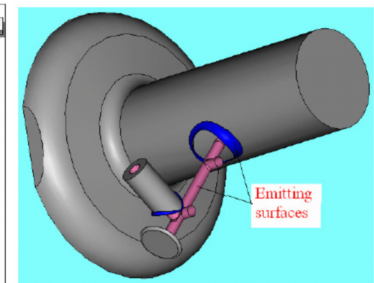
Simulation took ~1 day on 48 2.4GHz CPUs, with ~100k macroparticles/bunch

Electromagnetics

- Access to state-of-the-art codes through SciDAC
  - Develop local expertise
  - Provide simulation support to ILC crab cavity design
- Starting to get involved in wakefield calculations, to
  - Utilize in beam dynamics models
  - Cavity design support
    - Activity @ 0.3 FTE level, HIGHLY LEVERAGED!

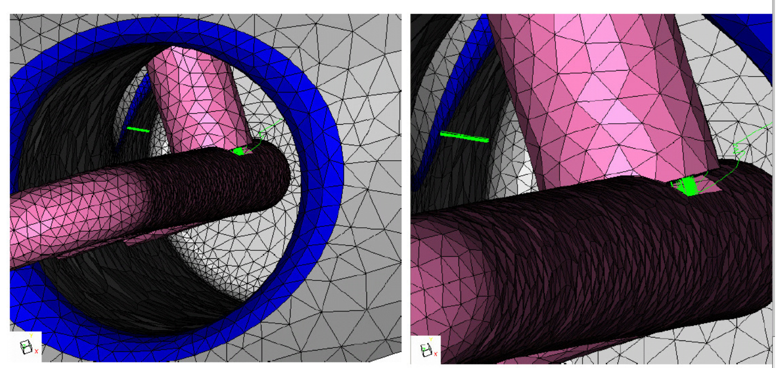
MP phenomena in LOM Coupler





Maximal value for ECF corresponds to the field level about 36 MV/m

MP in LOM Coupler at 46 MV/m



Questions?